Technical Report

UDC 669 . 1 : 658 . 274

Advances in Maintenance Management of Infrastructure Facilities in Steelworks

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Abstract

A steelworks is comprised of a great number of plant facilities of different types and scales. Since these facilities work under conditions more severe than those for other industries such as heavy loads, high temperatures, steam, corrosive gases and sea salt, they degrade at higher rates and in varied ways. For this reason, equipment management to keep them in good order, level the investments for their renewal and minimize their lifecycle costs is crucial for running a steelworks. The present paper outlines the practice of systematic equipment maintenance and presents improvement activities using crane runway girders and building roofs as examples.

1. Introduction

There are many types of infrastructure facilities in a steelworks that support the steel manufacturing equipment (see **Fig. 1**); they include plant buildings, machine foundations, roads, railways and port facilities (any one of them being hereinafter referred to as a steelmaking infrastructure). Steelmaking infrastructures have characteristics different from those for other fields of industry and society in general.

First, they are large in size and number: the total land area of all the steelworks of Nippon Steel & Sumitomo Metal Corporation is about 100 km^2, more than the area surrounded by the Yamanote Line, the circle railway line in Tokyo, and for this reason, a great amount of labor and cost are involved in their inspection, repair and other maintenance activities. Next, environmental conditions differ in different areas of a steelworks, and as a result, the rates of deterioration of the infrastructures differ significantly. In addition, owing to heavy loads, high temperatures, vapor, gases, sea salt, etc., which are not uncommon in steelmaking, the facilities deteriorate due to a variety of causes such as fatigue, thermal degradation, corrosion and wear.

Due to the great number of steelmaking infrastructures working under such conditions, how to improve the efficiency of the management of their maintenance is an important issue. Nippon Steel & Sumitomo Metal introduced the concept of condition-based maintenance (CBM) about 50 years ago, and ever since, has established maintenance management systems on this basis. CBM is a concept of equipment management first put into actual practice in the aircraft industry to reduce equipment maintenance costs in the 1990s, and then gradually spread to other fields of industry. It began at the time when the IT environment was still primitive; analog cameras were

Fig. 1 Civil engineering and building structures in steelworks premises

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used for equipment inspection and inspection reports were handwritten at that time. In the 1990s, when PCs and CAD and other tools became widely available, the field work efficiency improved remarkably.

The present paper describes the maintenance management of steelmaking infrastructures taking plant building roofs and crane runway girders as examples.

2. Outlines of Maintenance Management of Steelmaking Infrastructures

There are a great number of steelmaking infrastructures in the works premises totaling 100 km^2 as stated earlier; the total area of the plant buildings, for example, is larger than the land area of Tokyo International (Haneda) Airport. Such facilities are modified or expanded as steel manufacturing technology advances, and as a consequence, facilities of the same type in the same works are often of different specifications or types of structure depending on the time of construction. Different types of facilities such as blast furnaces, converters and rolling mills are arranged in a works hundreds of meters apart from each other in different environmental conditions, and they age at different rates owing to different causes.

Due to the large size of steelmaking infrastructures and their aging at different rates for different causes, if they are managed by break-down maintenance whereby damaged parts are repaired only after they break down, it leads to great business danger, which include things such as equipment failing unexpectedly and production lines stopping as a consequence, and many facilities coming to the end of their service life at the same time calling for a large capital investment within a short period, etc. According to another maintenance philosophy by which equipment is inspected and repaired at prescribed intervals, on the other hand, because of the largely different rates of degradation, some equipment units may fail at the end of their service life and cause problems, while others still sound are replaced with new ones before the end of the service life, leading to major investments and large losses because of the large number of facilities.

To efficiently maintain and manage steelmaking infrastructures of such an intrinsic nature, it is essential, in addition to having an adequate maintenance plan and practicing equipment inspection and repair following it, to establish a management framework for maintenance activities; that is to say, to analyze and evaluate as to whether the inspection and repair already carried out were appropriate, and change the methods of inspection and repair where necessary. This management of maintenance can be summarized as follows:

(1) Inspection and repair plan
- Definition of the equipment units to be inspected and the method of inspection for each of them
- Definition of the equipment units to be repaired and the method of repair for each of them

(2) Field practice
- Inspection and maintenance according to the inspection and repair plan

(3) Feedback of inspection and repair plan and actual field practice
- Analysis and evaluation of the inspection and repair plan

(4) Improvement of inspection and repair plan and field practice
- The inspection and repair plan and the field practice are reviewed and improved according to the evaluation results

For efficient and effective maintenance practice following the above procedures, it is necessary to prepare equipment maintenance standards to minimize fluctuation in work quality among the personnel in charge and establish support systems capable of processing a huge amount of data adequately as intended. The equipment maintenance standards, which specify the target equipment and the manner of inspection and repair, constitute the core of maintenance management, and as such, set forth the rules for the field practice of inspection and repair. The support systems, on the other hand, must provide two functions: a mapping function to classify plant facilities in different areas according to specification, structure and work conditions based on the evaluation indices set forth in the equipment maintenance standards; and an analyzing function to judge the service life, the rate of degradation and the degree of importance in the manufacturing process, or the importance factor, of each of the facilities. Nippon Steel & Sumitomo Metal has improved and upgraded these equipment maintenance standards and the support systems for some decades.

The outlines of the equipment maintenance standards and the support systems are explained in the following Section 3 using examples of typical steelmaking infrastructures, i.e., crane runway girders and roofs of plant buildings.

3. Formation of Maintenance Management of Steelmaking Infrastructures

3.1 Crane runway girders

A typical crane runway girder (CRG) is illustrated in **Fig. 2**. Its important function is to support heavy loads, and to minimize the risk of its breakage, in which event, overhead cranes that travel on it must be stopped and the production is delayed, or in the worst case with CRGs for cranes handling ladles of molten metal, a severe accident such as the spilling of molten metal may take place. In most cases, damage leading to CRG failure originates from fatigue cracks, and for this reason, it is essential to identify cracks and take adequate remedial measures at an early stage.

3.1.1 Equipment maintenance standard

The equipment maintenance standard for CRGs consists of evaluating degradation to classify each girder unit by deterioration ranks, and specifying the methods of inspection and repair of the units according to the rank.

Figure 3 shows deterioration ranks and necessity or otherwise of inspection and actions to be taken for each of the ranks. The deterioration rank is defined based on the cumulative fatigue index (internally called D), which is calculated from the travelling frequency and load of the crane, and CRGs are classified into the following four ranks: when D of a CRG is 1 or less, it is classified into Rank 4; when D is larger than 1 and when no cracks are found at inspection, it is classified into Rank 3; when a crack is found, it is classified into

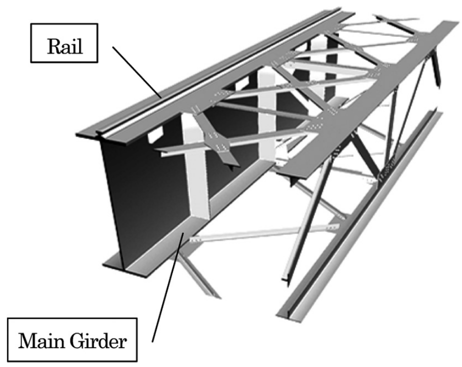

Fig. 2 CRG

Deterioration Rank	Inspection	Actions to Take
Rank 1 Serviceability Limit (Repetitive Cracking)	Required	Fundamental Measures (Replacement or Reinforcement) Required
Rank 2 Crack Initiation	Required	Welding Repair +UIT
Rank 3 Unsound State [Target:D>1]	Required	UIT
Rank 4 Sound State [Target:D1≦1]	Not Required	-

Methods of inspection and repair defined according to deterioration rank

Fig. 3　Maintenance management criteria for CRGs

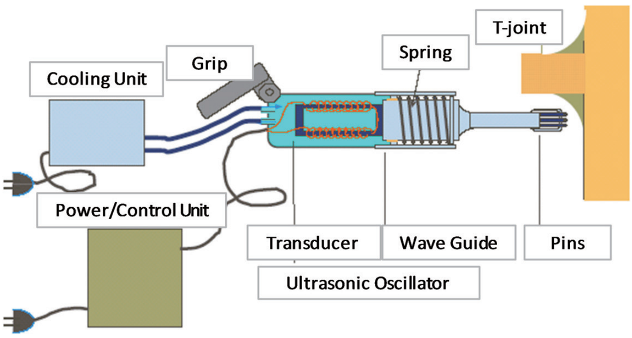

Fig. 4　UIT

Rank 2; and when a CRG is found to have been broken or there is a repeated crack, it is classified into Rank 1.

If a CRG is classified into Rank 1, it is replaced with a new one according to the schedule, and for a CRG of Rank 2, the crack is repaired; in addition, application of the ultrasonic impact treatment (UIT), [1] which is illustrated in **Fig. 4**, is recommended. The UIT is a method for applying compressive residual stress to steel structures, improving the shape of weld toes and hardening surface layers, and by so doing, upgrading it in terms of fatigue strength classes and reducing fatigue to extend its fatigue life. Since CRGs of Rank 3 are likely to develop cracks, the maintenance standard prescribes the UIT as a measure of preventive maintenance.

Next, how to find fatigue cracks by inspection is explained. The ease with which a fatigue crack occurs depends on the shape of the weld joints and the method of post treatment. **Figure 5** shows typical examples of fatigue cracks of CRGs. Cracks are likely to develop at portions such as the welded edge of a bottom flange, the lower end of a triangular rib and the weld joint between the top flange and the web. In addition, if reinforcing plates or braces for catwalks, piping or cabling are welded to the lower surface of the bottom flange, or a cover plate is welded to repair some defect, cracks often originate from such weld joints. In consideration of the above, weld joints are specified in equipment maintenance standards as parts to be inspected.

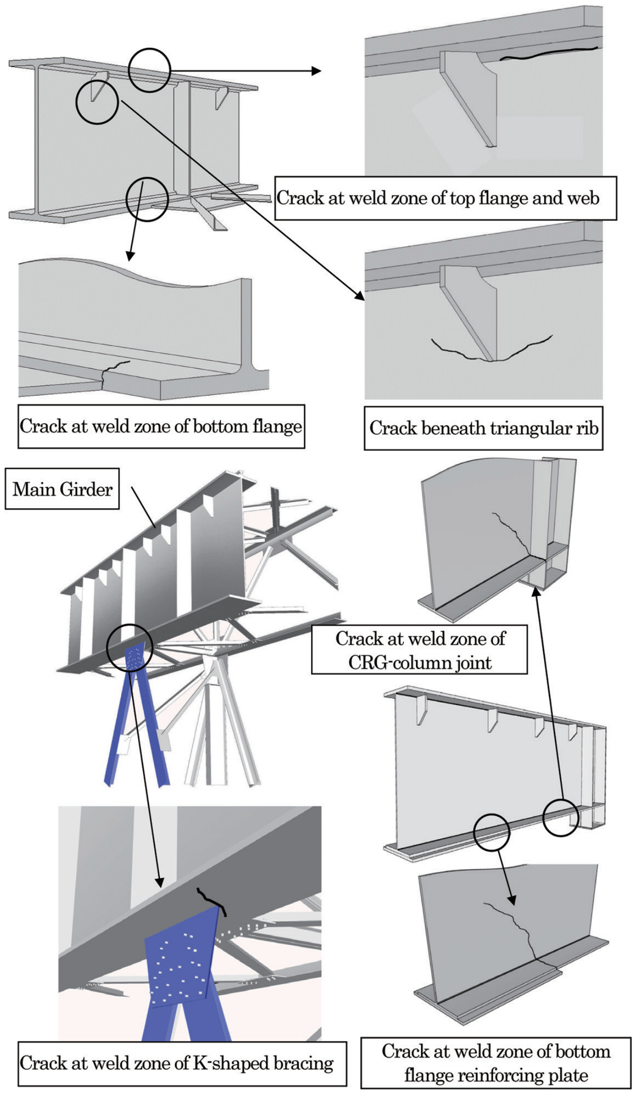

Fig. 5　Portions of CRG prone to crack development

The importance factor is defined for each CRG in consideration of the type of crane load (molten metal, etc.) and the existence or otherwise of alternative routes or means of transport, and based on this and the deterioration rank, the interval and the method of inspection are specified. For instance, whereas stages are provided for CRGs of a high importance factor for close visual inspection and periodical non-destructive tests, those of a low importance factor are inspected visually from the plant floor.

Figure 6 shows some examples of the results of inspection based on the above rules of equipment maintenance. The frames represent the results of the three latest crack investigations at 16 weld joints on the lower face of a bottom flange. This particular CRG had no cracks and was classified as Rank 3; this is only one example of roughly 10000 CRGs of all the steelworks of the company. Such data are stored electronically and used as they are or in the form of paper prints. Such data show the soundness of each equipment unit from time to time, but do not give the prospects for the future. Here, another important part of equipment management, namely the support systems, comes into play.

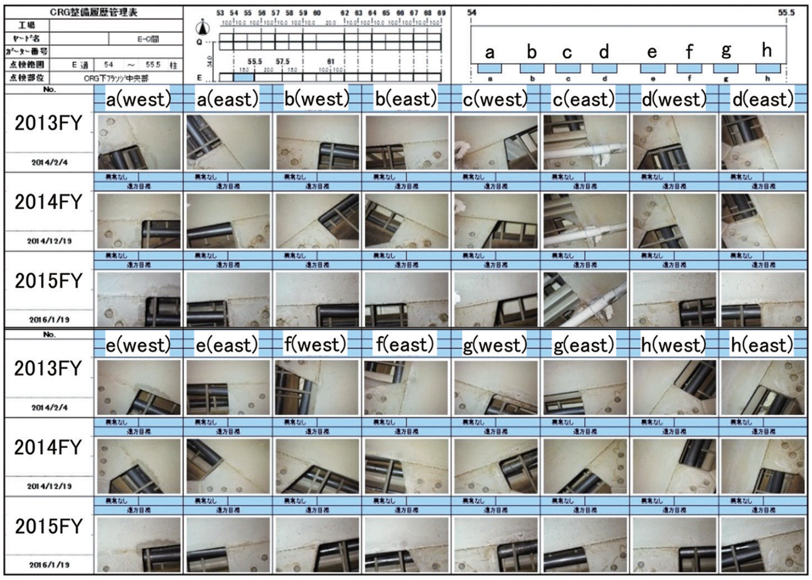

Fig. 6 Examples of CRG inspection results

3.1.2 Support systems

CRGs are different not only in age, span and structure, but also in operating conditions such as the frequency of crane travel, the weight of the load and its position. To take all these factors into consideration, each CRG is given a unique address, and a ledger of CRGs as shown in **Fig. 7** is prepared. The year of construction, the number of crane travels per day, the stress imposed on the CRG by crane travel, etc. for each unit are input to it, and based on these data, the cumulative travelling time and D (cumulative fatigue index described in 3.1.1) are calculated automatically for each CRG. Then, with the input of the existence or otherwise of cracks at the latest inspection, the deterioration rank of the CGR is defined.

Figure 8 shows the deterioration ranks of all CRG units of an example plant building complex; here the ranks defined as above are given in different colors. Based on the deterioration rank and the importance factor, the deadline date for the next inspection is automatically specified, and if the inspection is overdue, an alarm is given; this mechanism is effective for avoiding inadvertence in the planning and execution of inspection. Using this method it is possible to understand the overall situation of all CRGs of a plant com-

Linked with MAP | Input Data

Code (Address)	Name of Yard	Equipment Importance Factor	Construction Year	Length (m)	Frequency of crane travels (/day)	Imposed stress (MPa)
A1	X Yard	SA	1969	20	100	180
…	…	…	…	…	…	…
B1	X Yard	A	1975	20	50	170

Calculation in EXCEL®		Inspection Result		Judged in EXCEL®	Calculation in EXCEL®	Judged in EXCEL®
Cumulative crane travels (*1)	D Value (*2)	Inspection Date	Crack existence	Deterioration rank (*3)	Next inspection date (*4)	Alarm
1,715,500	6.0	2015/11/15	exist	2	2016/5/15	Overdue !
…	…	…	…	…	…	…
748,250	2.5	2015/11/15	none	3	2016/11/15	

*1 Calculated from Construction Year and Frequency of crane travel
*2 Calculated from Generated stress and Number of repetitions
D Value : Cumulative fatigue damage
*3 Judged from D Value and Crack existence
*4 Calculated from Deterioration rank and Equipment Importance Factor

Fig. 7 Management of CRG data by EXCEL®

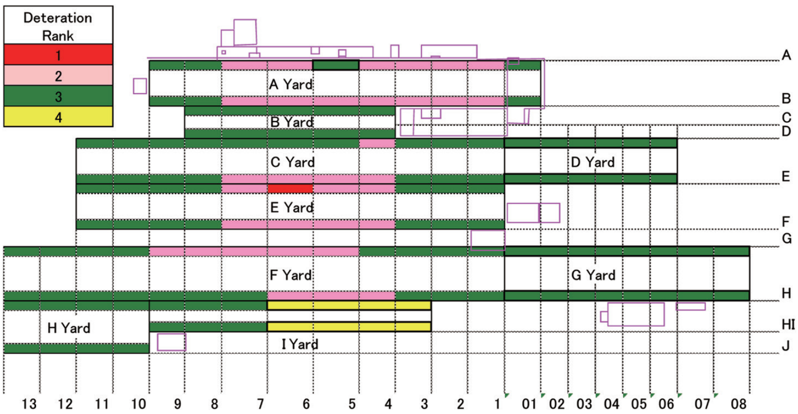

Fig. 8 Example of color-coded plan for one management block of CRG in the mapping system

plex at a glance, and the timing and extent of repair of each CRG are programmed in consideration of the overall balance and the distribution of deterioration ranks.

The maintenance management based on the equipment maintenance standards and the support systems explained above has proved effective at preventing serious problems of CRGs.

3.2 Roofs of plant buildings

3.2.1 Equipment maintenance standard

The equipment maintenance standard for building roofs consists of deterioration judgement criteria and specification definition criteria.

The deterioration judgement criteria are the rules by which the degree of deterioration of metal roofs is judged according to the following deterioration steps: sound state; paint layer degradation; base metal corrosion; and perforation corrosion. The criteria are effective at eliminating variation in evaluation. In coastal areas, for example, building roofs are damaged by sea salt, and that of a hot rolling mill plant by the great amount of water vapor arising from water cooling of hot slabs during rolling. In places where there are such corrosive factors, the deterioration rate of building roofs tends to be high, and the criteria make it possible to distinctly judge the stage at which a specific roof is.

The specification definition criteria, on the other hand, specify metal material and coating paint for roof repair in consideration of expected service life in different environmental conditions, life cycle costs and environmental factors such as vapor and gases. The performance of roof material and coating paint is evaluated through tests when necessary. **Figure 9** shows specimens that underwent a cyclic corrosion test conducted indoors: the top four frames show the change of a specimen of a new roof, the middle frames the same of a roof after use, and the bottom frames the same as that of a used

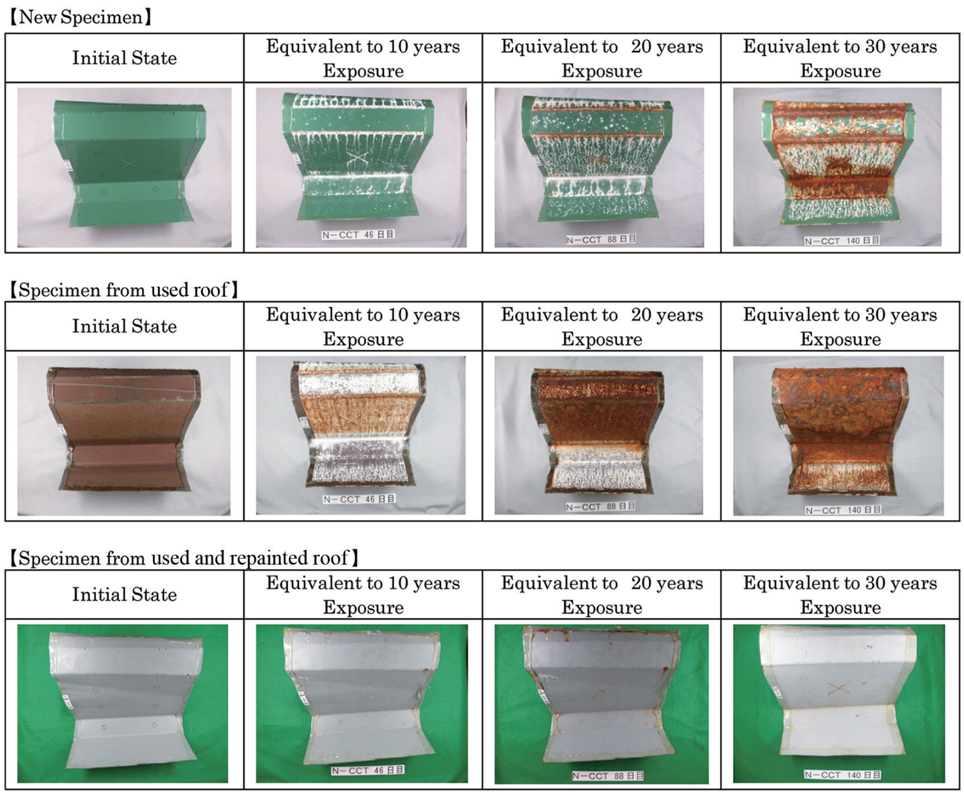

Fig. 9 Environmental cycle test for optimization of life-extension paint

and repainted roof. These photos demonstrate the weathering resistance of each specimen. The equipment maintenance standard specifies the portions to be inspected, the frequency and method of inspection, and the method of repair based on the deterioration judgement criteria and the specification definition criteria.

3.2.2 Support systems

To understand the general deterioration trend of a large-expanse roof and the relative degrees of deterioration of different portions, it is necessary to use a mapping system whereby the entire roof of a building is divided into a grid and the information on the aging is controlled section by section of the grid.

Figure 10 shows an example of such a mapping. The area of the roof is divided into control sections according to the lines of building columns, each control section is given an address, and the deterioration information obtained through inspection is input address by address. This was done manually on paper forms up to the first half of the 1980s, but a unique mapping program package has been developed by incorporating the macro function of Microsoft Excel® and customization of commercial mapping software packages.

3.2.3 Example of maintenance management practice

Figure 11 shows an example of the deterioration prognosis of a building roof. The most suitable materials are selected from among those available at the time of construction for building roofs in consideration of the use condition and life-cycle costs and according to the technical advance in manufacturing of base sheets and surface treatment; steel sheets with paint or fluoro-resin-coating, stainless steel sheets, galvanized and galvalume steel sheets have been selected for plant roofs. The rate of deterioration differs depending on the roofing work method, painting work (works painting or site painting), steel grade, coating specification and the environmental condition. The rate of deterioration and the expected service life are estimated for each grid section in consideration of the above and the records of past inspection.

Figure 12 gives an example of comparative investment simulation; the vertical axis of each graph represents the roof area, the horizontal axis time (in years), and the colored belts the percentages of different degradation ranks. The left-hand graph shows a case where the roof is renewed in the entire area, and the one on the right-hand another where the same investment amount is divided into 70% renewal and 30% repainting. As the graphs show, the latter case is better than the former, because the percentage areas of deterioration ranks 1 and 2 (red and pink, serious deterioration) are smaller.

Figure 13 shows an example of the mapping. All management blocks are automatically colored differently according to the deteri-

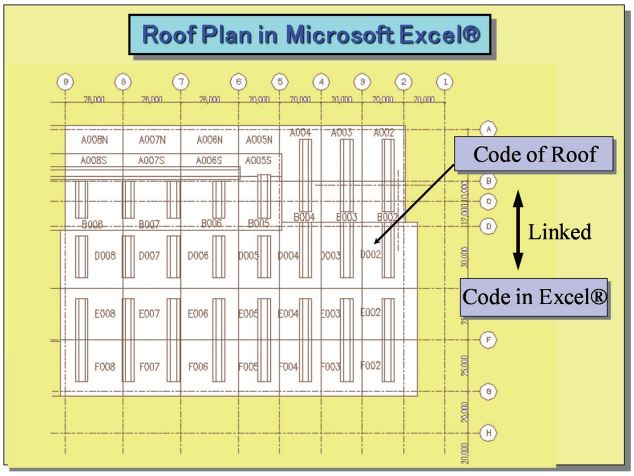

Fig. 10 Coding of roof by the mapping system

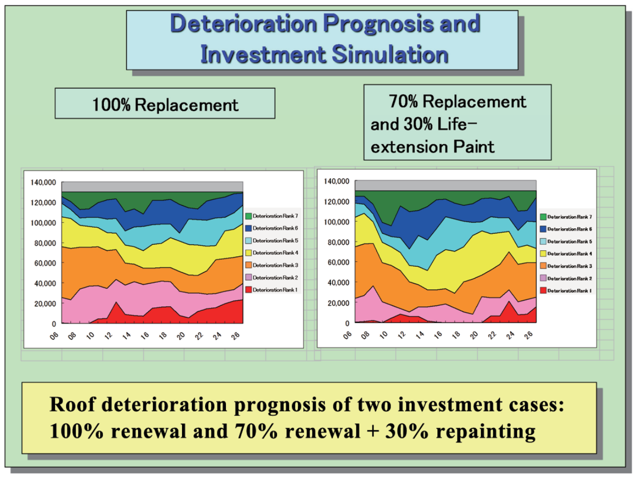

Fig. 12 Prognosis of roof deterioration for investment simulation

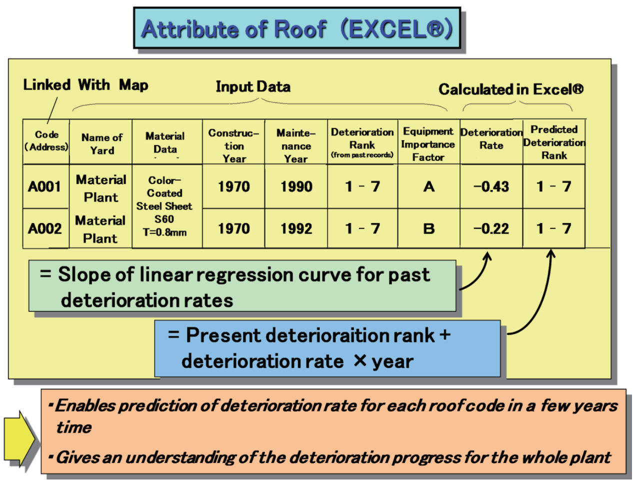

Fig. 11 Deterioration rate prognosis of roof

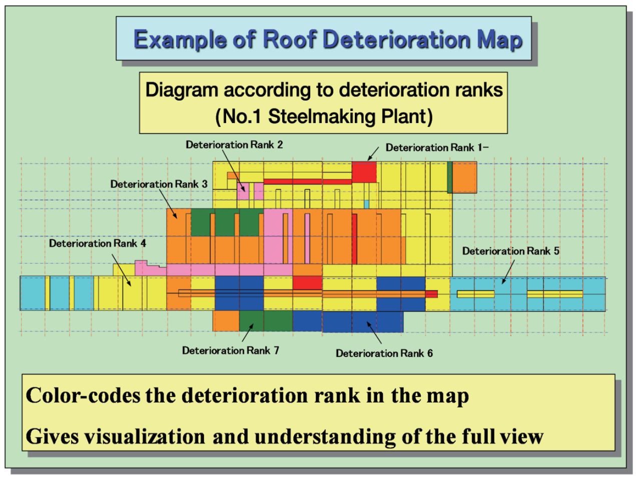

Fig. 13 Color-coded mapping of plant roof divided into management blocks

oration rank, and the timing and expanse of repair are determined in consideration of the distribution of deterioration ranks at present and in the future. This system is useful also for deciding whether the specifications of a short-life portion have to be changed locally at the time of repair. Note that similar color maps can be produced as required according to the year of construction, difference in specifications, importance factor, priority order of repair, etc. Thanks to this, an enormous quantity of data is made visually and easily comprehensible, which supports efficient and systematic maintenance activities.

4. Improvement of Maintenance Management

4.1 Improvement of inspection efficiency

Until some time ago, the inspection data of CRGs described earlier were manually recorded on field notes, brought to the office, where they were input electronically, and photographs were pasted to relevant areas of the inspection record after confirming the locations where they were taken. This was very troublesome because of the vast data amount, and an improved method has been developed as explained below.

Figure 14 shows a scene where inspection data is input on the spot into a tablet terminal, and **Fig. 15** another where a photograph taken by a digital camera is wirelessly sent to a tablet terminal, and pasted to the prescribed frame of the inspection record. By this, the data input and the inspection record preparation work in the office can be skipped, and inadvertent omission and error are eliminated. This method was first applied to CRGs and will be expanded to other types of facilities.

4.2 Upgrading of support systems

The support systems for CRGs and the roofs of plant buildings were individually developed using EXCEL® and operated by the organizational units responsible for the plant in question. Recently, to cover an entire works by a single data processing system and improve the linkage of inspection data with other maintenance management documents, the maintenance support systems are being customized based principally on NaviPortal®, an equipment management software package commercially available.

Figure 16 is an example screen that uses the package; it comprises the following areas: (1) displaying the facility management diagram; (2) displaying the facility management ledger by EXCEL®; (3) setting the conditions for mapping and color coding; (4) displaying documents linked to a chosen address; and (5) displaying the files conforming to the desired search parameters. This screen, therefore, makes it possible to access any desired information and document with high efficiency.

Figure 17 shows a facility management diagram being created. A 3-D model of an entire plant building complex can be produced using Sketchup Pro® or a similar program package for generating 3-D models, and roofs, CRGs, building walls, crane rails, rain gutters, and building fixtures are sorted and addressed in an equipment management diagram according to individually defined management blocks; this way, it is possible to control in a unified manner different types of equipment units that were once documented in

Fig. 14 Input of inspection results using a tablet computer

Fig. 15 Data transfer from digital camera to tablet computer

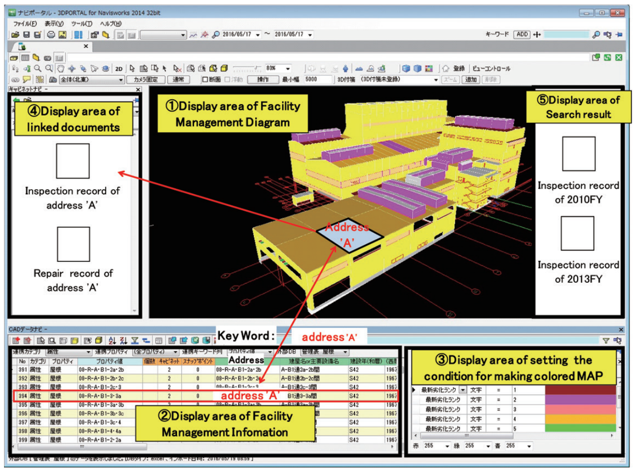

Fig. 16 Screen configuration of NaviPortal®

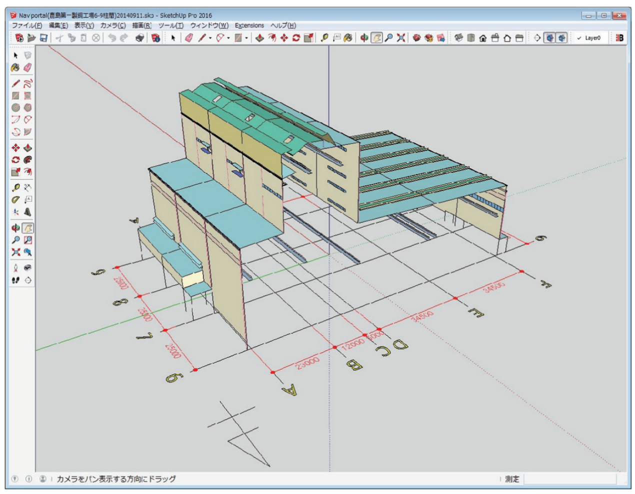

Fig. 17 Creating a facility management diagram in Sketchup Pro®

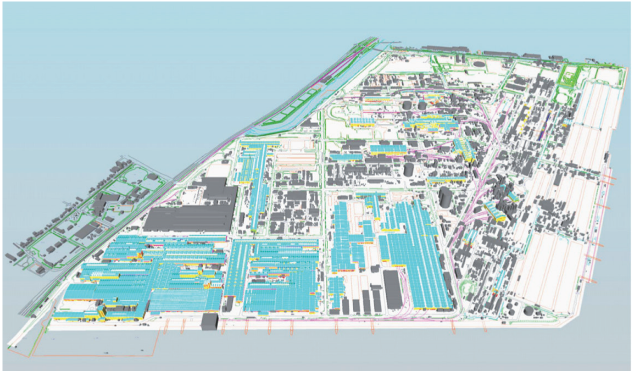

Fig. 18 Maintenance management of steel plant infrastructures using NaviPortal®

separate files.

In addition, NaviPortal® is capable of dealing with information in the facility management ledger by EXCEL®, and thus it is possible to classify facilities by color coding automatically according to deterioration ranks by linking the address of each equipment unit to the facility management diagram. The conditions set at the time of the map preparation can be modified or new conditions added through the screen, and maps of any desired forms can be created as required.

It is possible, in addition, to display information related to a desired address in the area (2) linked to the facility management ledger simply by selecting the address in the area (1) for the facility management diagram, and easily link inspection records and other documents to the address, and display them. Further, any of the addresses can serve as a search keyword, all files in a selected folder are searched, and the documents containing the address are displayed in the search result area, which makes it easy to search related documents such as inspection results and repair history. **Figure 18** is an overall view of an entire steelworks using the support system based on NaviPortal®. Studies are under way to expand this system to all infrastructures of an entire works.

5. Closing

Maintenance management of steelmaking infrastructures and its upgrading were explained herein, referring to examples of crane runway girders and plant building roofs. Civil engineering and building specialists of steelworks consider it imperative to further enhance the efficiency of the maintenance management systems for the infrastructures in accordance with the advance of IT technology. Over the last few years, the construction industry introduced many advanced IT measures and techniques such as BIM, CIM, AR, robots and drones, and the steel industry must make more use of these fruits of technical advance actively to enhance the efficiency of equipment maintenance.

Acknowledgements

The systematic maintenance of Nippon Steel & Sumitomo Metal has been realized through many years of close cooperation with contractors working inside the works premises. We would like to express our appreciation and profound gratitude to the people of such contractors who have helped devise maintenance standards and guidelines, who exerted efforts to improve and upgrade the maintenance systems, and who inspect and repair the works infrastructures every day.

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